CRITICAL NATIONAL NEED IDEA

High Accuracy LOcation (HALO)

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1. Introduction

We write this whitepaper in support of a technology innovation program enabling a High Accuracy Location (HALO) infrastructure for the nation's roadways. We see the realization of HALO as a fundamental building block for our transportation future, be it vehicle-highway automation, novel concepts in electrification or road safety.

The safety and efficiency of our Transportation Infrastructure has been a high priority for transportation agencies at all levels of government (7). Each year, approximately 40,000 Americans are killed in automobile accidents, and another 5,000,000 injured. In an estimate by the U.S. Department of Transportation, the lost productivity due to traffic congestion alone is some $100 billion per year--not even including the cost of wasted fuel and pollution. The history we recount below shows one hurdle to overcoming these problems is the lack of a precise and ubiquitous positioning infrastructure for our nation's roadways.

As early as 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) charged the Secretary of Transportation to design and prototype a fully automated highway system able to revolutionize the safety and productivity of the national highway system. The National Automated Highway System Consortium (NAHSC) developed vision and magnetic marker based lane keeping as the importance of precise positioning came to be quickly appreciated. In 1995, NHTSA's report to Congress showed that 90% of the road accidents today could be at least partially attributed to driver decision error. Recognizing the opportunity to save lives even without full automation, Congress continued funding NHTSA to enable intelligent in-vehicle warning systems targeted to ameliorate these crashes with real-time driver alerts in critical situations. As these Congressional imperatives bore fruit, the first generation of safety system research prototypes emerged based on sensors such as radar, lidar, and vision systems to detect neighboring cars. It was quickly realized that knowing the roadway environment, such as its geometry, upcoming curves, cars around intersection corners, or signage, was critical to the operation of safety systems. Much of this is beyond the sensor field of view. Research seized upon the idea of mapping all this information and recovering it in real time by precise GPS positioning and map matching[1] Eighteen years after the congressional mandate, these systems remain impossible because available digital maps[2] are not accurate enough and GPS fails in too many places to have safety rely on map matching.

Nevertheless, driven by the desire to save lives, the scientific interest in GPS-based AVSS has grown even more, as the cost of sensor based systems remained high, and the cost of WiFi started to tumble. Government and industry came together under the aegis of the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications to research Cooperative Vehicle Safety Systems (CVSS). In the CVSS concept, potentially a cheap and therefore quick pathway to the saving of lives, each vehicle broadcasts its GPS position and speed to neighboring vehicles. The receiving vehicle subtracts the received position from its own, determines if there is a threat, and informs its driver. Thus getting CVSS into people's cars relies critically on two capabilities – the ability to always, reliably know one's position in the GPS coordinate system, and vehicle-vehicle, roadway-vehicle wireless communication. An entire body of literature, to which we has a strong contribution (e.g., 9,10,11), strongly supports the following thesis: Precise positioning and local wireless communication can save lives. In fact, we built the world's first CVSS prototype able to deliver warnings on sub-second timescales (10). The rise of smartphones has made the thesis even more compelling. Bicyclists, elderly pedestrians, or the blind could carry WiFi based phones sending messages to cars when they cross the street, i.e., an extension of the CVSS concept to safeguard those most vulnerable on the road. Our testing shows the WiFi works but the positioning fails. GPS is simply not good enough in urban environments. The mask angles are too poor due to the built environment. The *2008 Federal Radionavigation*

[1]http://www.nhtsa.gov/portal/nhtsa_static_file_downloader.jsp?file=/staticfiles/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2004/FinalRept_111904.pdf

[2] IVI Light Vehicle Enabling Research Program. "Enhanced digital mapping project final report", 2004.

Plan, under signature of Secretary Gates and Secretary Peters recognizes the criticality of accurate positioning for these safety systems on page 4-24. Moreover the final report by U.S. Department of Transportation, Volpe Center, on the *Vulnerability Assessment of the Transportation Infrastructure Relying on the GPS*, recognizes the danger of relying solely on GPS. The purpose of the HALO infrastructure would be to make precise positioning ubiquitous merely by filling in the GPS gaps. Secondarily, it could be extended to provide GPS backup based on infrastructure security assessments (5)(8).

The final report of National Surface Transportation Infrastructure Financing Commission[3] submitted to the Honorable vice president Biden and Honorable house speaker Pelosi opines that the VMT fee system needs to be the fulcrum of highway financing in the future. Price signals enabled by the current gas-tax based system are too weak. In the VMT fee philosophy drivers pay directly based on when and where they drive. High Occupancy Toll (HOT) lane systems required to evolve into this future, require a vehicle to be positioned with lane level accuracy. This is currently only possible with gantry based RFID systems. This is expensive. We seek research able to make HALO a cheaper option by building a GPS++, i.e., a complementary technology filling in GPS gaps so that transportation system operators can build HOT lanes when and where needed.

Getting to this future, requires a combination of wireless communication and radio-location services. USDOT has responded admirably to the wireless communication axis of these value propositions. We argue for the need to act energetically on the positioning axis. Through initiatives such as the acquisition of DSRC spectrum, VII (Vehicle Infrastructure Integration) and VSCC (Vehicle Safety Communications Consortium) programs, the department has built national momentum behind DSRC wireless that is today equally powered by corporate America. We ask that the current funding opportunities at NIST be an opportunity to seed equal momentum for precise positioning. Safety demands reliability. In this lies the case for federal investment. If the public is to be offered safety through precise positioning, the infrastructure must be reliable and be publicly understood to be gradually growing to be present everywhere. Thus it needs to unfold to a national plan evolved at the federal level.

2. Research Requirements and Government Support

Delivering ubiquity, in many cases, entails massive investment. Therefore the fundamental research challenge is to discover the means to precise positioning nationwide with moderate investment. The opening of the GPS satellite constellation to civilian use in 1978 spawned a dramatic expansion of the original technology base. Thousands of creative minds found products saleable in the marketplace, to grow the accuracy and reach of this DoD service. The path to realizing the goal with moderate investment lies in a national plan, which brings within its ambit, products from the GNSS market, even while recognizing the matter cannot be left entirely to its invisible hand. Figure 1 illustrates this philosophy. There is enough in the current literature to make the case that wireless communications and precise positioning brought together for safety systems, can save lives. The HALO research plan, which will primarily address the accuracy and reliability requirements of positioning for ITS systems, will play an important role in the current administration's commitment to rebuild and renew the core infrastructure. HALO can accelerate the goals of the E-911 program. E-911 is still far from the accuracy envisioned by FCC. In the longer term, HALO can be a critical enabler for a vision such as Automated Electric Transportation. The convergence of the nation's energy and roadway grids could unleash the greatest jump in productivity seen since the building of the Interstate Highway System and wean the nation off foreign oil. The ability to know position precisely will greatly simplify the problem of designing control systems spanning these two networks.

[3] "Paying Our Way: A New Framework for Transportation Finance" prepared in response to Congress's charge in Section 11142 of the Safe, Accountable, Flexible, and Efficient Transportation Equity Act

The global positioning system (GPS) has been developed and deployed by government. Extending the coverage and accuracy of GPS has been for years the objective of much private sector research and deployment efforts. For example, technologies such as DGPS, GPS-WAAS, GPS+INS, GPS-RTK, and network RTK have been developed in recent years and are partially deployed. Limited coverage pseudolite based systems (e.g., developed by Locata) are also available. However, to this day no system has been proven to be able to ubiquitously provide accurate positioning information, in particular for advanced ITS infrastructures. In most case, such as with GPS-RTK, the cost of the positioning system has prevented wide scale deployment. Moreover, these technologies rely on GPS, and only work well in areas where GPS reception is not weak. In areas such as urban canyons and forested streets, these systems will not be functional either. Pseudolite based solutions which can cover these dark areas are also limited in range and are not yet ready for prime time.

In addition to technological difficulties, the deployment of HALO requires significant government support and funding, which has discouraged private sector from aggressively attempting to resolve the technological issues. Overcoming the current technological hurdles and enabling HALO, therefore, requires government supported research and development initiatives.

The Consequence of Inaction on developing the positioning technology and infrastructure for advanced ITS is continued economical and environmental losses as well as transportation related injuries and fatalities, which in turn have further economical and societal implications. These burdens are among the most serious to the US economy, environment, public health and quality of life.

The commitment of the current administration to finding renewable energy sources are equally matched by the requirement for more efficient transportation systems. Similarly, the commitment to reducing the health care costs will also include efforts in reducing traffic related injuries and fatalities (~43000 fatalities, 5 million injuries, per year in the US) and their consequent effects on the overall health care and insurance systems.

Essentials for TIP Funding: In USDOT research programs, funding allocations do not appear proportionate to the size and criticality of the positioning problem. For example, this year's Exploratory Advanced Research Program of the Federal Highway Administration (FHWA) which currently targets "Intelligent Transportation" projects, announced up to $650,000 for the Next Generation Positioning technologies, putting it well behind other ITS projects such as Behavioral Science Approaches for Best Practices for Alternative Highway Revenue Collection ($2,000,000).

The National Science Foundation (NSF) continually funds small projects that develop the signal processing theory and algorithms to enable a cheaper HALO. However, no program exists to the best of our knowledge on applying this scientific research to the high accuracy location problem for pedestrians, bicycles, or cars.

Despite the critical and pressing need for HALO, reported by government reports such as the 2008 Federal Radionavigation Plan (page 5-22), current research funding opportunities do not match the need.

Audience for the possible funding opportunities: The federal government funding for developing the HALO system should target two different sectors, academic institutions that will develop the scientific base of the HALO technology and the private technology sector which will enable the eventual development of viable positioning technologies in collaboration with academic institutions. Substantial deployment of the HALO system, however, will require substantial federal and state government funding and involvement, and may not be targeted by this funding program.

3. The Envisioned Research Path

We identify two main research tasks that must be undertaken in order to develop the high accuracy location for national civil infrastructure:

Nationwide Positioning Infrastructure Cost Assessment – to address the challenge of estimating the geographical extent of the new infrastructure. A perceived solution should achieve this goal without driving all the roads in the country as has been done at considerable cost, and little output, by the mapping companies. We see estimating the road area where GPS and its derivatives fail to meet safety system requirements, as the first step to estimating the amount of national investment required to make positioning services available everywhere for safety. Since almost all Global Navigation Satellite Systems (GNSS) work by communications in some spectrum between infrastructure and receiver, the proposed research must also deliver a national spectrum plan, addressing the challenges of nationwide inter-operability and reliable communication in safety-critical situations without excessive licensing or spectrum usage fees, or excessively low power operation.

Figure 1 illustrates the systems engineering approach. Suppose GPS is accurate enough for precise positioning on V% of the nations roads, GPS+WAAS in the market does another W%, emerging GPS + Network RTK adds another Y%. To a first approximation, V+W+Y can be seen as that percentage of the national roadway always exposed to 5 or more satellites at all times[4]. Of the remaining road segments, i.e, segments falling below the 5 satellite threshold, some are small enough for a vehicle to pass without losing precise positioning by GPS/INS/Vision integration (22). Then the new national positioning investment dollar, needs to cover the road area percentage 100 – (V+W+X+Y). The smaller the new investment area, the "dark area" marked HALO in figure 1, and the cheaper the technology required to cover it, the more attractive the new positioning investment - a big bang for the small buck. This is the expected impact of this research - the case for federal investment on precise positioning for the nation's roads.

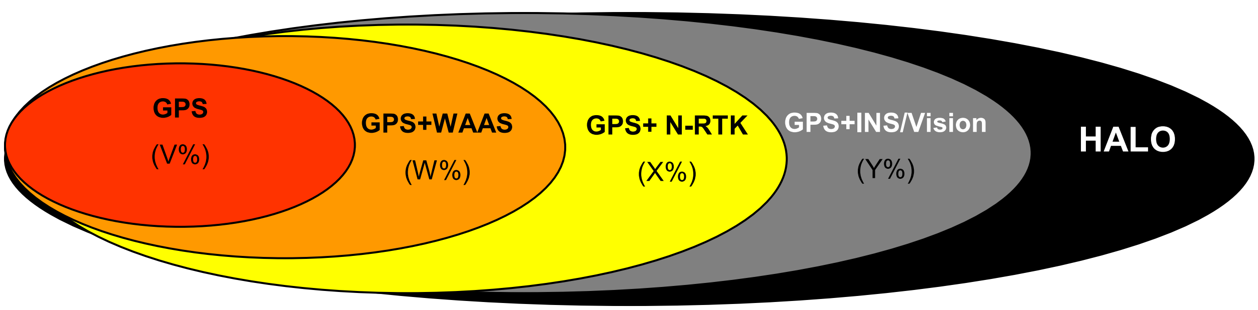

Figure 1. The basic approach to precise positioning for safety nationwide

The mapping companies have driven the nation's roads. In spite of this, the data needed to identify GPS gaps does not exist. Instead of driving all the nation's roads, a possible solution can be developed based on a random sampling methodology on GIS maps fused with a PDOP (Position Dilution of Precision) coverage model. Basically, GPS precision is related to satellite visibility (see for example (11)). The satellite visibility is related to the mask angle. The mask angle is related to height of roadside buildings and trees. The idea is to model these relationships and apply them to GIS maps we have found with the necessary information.

[4] Roughly a mask angle of 45 degree or less after occlusion by trees or building.

Developing a ubiquitous HALO technology for advanced ITS – Given the multitude of positioning technologies currently available, the research plan for developing the new HALO technology must address the challenges of quantifying state of the art technologies such as GPS+WAAS, GPS+RTK, pseudolites, and RFID in real driving conditions on real roads and perhaps fusing them in a comprehensive solution enhanced with yet unexplored technologies. In particular, we expect the new technologies be developed based on pseudolite systems specially deployed for transportation infrastructure. There are several challenges here. Current pseudolite systems require precise initialization and highly sophisticated signal processing to overcome multipath (1) and achieve clock synchronization (2) (3). One possible solution is to overcome these problems using methods such as augmenting pseudolite designs with RFID readers and tags (13), and phased array antenna's used to estimate angle of arrival (4)(12). This relaxes the picosecond clock accuracy requirements though it does require more precise phase measurements. One approach to address this problem is the use of virtual phased arrays (4)(12).

There are two basic methods of multi-lateration. Either one measures distances to a set of reference base stations or satellites or one measures angles. GPS and pseudolites basically do distance measurement. They maintain highly synchronized clocks across the reference stations and derive distance through Time Difference of Arrival (2)(3). Our basic idea is to add positioning based on angle. This is practical today because of the advances in DSP hardware and phased array antennas (4), demonstrated, for example, by the rise of MIMO OFDM (IEEE 802.11n) as a WiFi product. We expect HALO technologies bring the power of this new class of chipsets to precise positioning (12)(13).

Augmenting pseudolites with Angle of Arrival (AoA) estimates derived using phased array antennas should cut cost by significantly reducing the need for highly precise clock synchronization (2) (3) and resolving multipath through angle of arrival measurements (4). The power of the AoA approach lies in the ability to combat multipath interference (1). In particular, sophisticated array processing algorithms should allow the receiver to compute the angles of all incoming rays: both the line-of-sight path and the reflected waves (1). Furthermore, by measuring the angles of multiple pseudolites, and collaborating with other receivers, it should be possible to isolate the line-of-sight path, thus reducing the effect of the multipath. If the reflected waves are independent in space, the receiver will be able to deduce which set of angles are consistent with one other, and thus the direct waves. One challenge in implementing phased array antennas is the spacing of the antennas which are in the order of the wavelength of the signal (in the order of ~30cm for 1GHz carrier). This may be problematic if such antennas cannot be integrated in the body of the vehicle or the on board unit. If faced with this issue, one can approach it by leveraging mobility to create a virtual phased array antenna by sampling at different time instances using one moving antenna (12).

Obtaining Radio Location Spectrum: 12 MHz of M-LMS spectrum is licensed to private companies. Skybridge and Telesaurus, partners of this whitepaper, hold the A-block M-LMS licenses, 6 MHz of bandwidth in total, in 80% of the nation including most all large markets. They have been for years and remain committed to using this spectrum for HALO+ITSCom. 12 MHz adjacent to this A-block M-LMS spectrum is the N-LMS spectrum; it is currently available for licensing to ITS wide-area communication projects, such as envisioned for HALO+ITSCom, where the deployment has participation or sponsorship of a government agency, as we envision for HALO+ITSCom. Combined, this will provide 18 MHz in the LMS band, at the permitted high power levels (30 Watts ERP) and at a mix of high base station transmitter heights in M-LMS (thus, best used for very wide area coverage in many or all directions) and lower heights for M-LMS (best used along major roadways, with directional antennas focusing signal along the roadways).

In addition, Skybridge and Telesaurus have obtained from the FCC much of the licensed spectrum in 217-222 MHz in 80% of the US, including most all of the more rural areas, to complement the LMS spectrum for HALO+ITSCom: this lower, 200 MHz range spectrum, at the unlimited transmission heights and hundreds of watts ERP power permitted, will provide especially long range coverage to enable more rapid, full, and cost effective ITS wireless in the majority of the nation which is rural, at least for certain core functions which can be supported by the available bandwidth. This spectrum will be put at the disposal of HALO\

4. Expected New Outcomes and Capabilities

We expect the result of the research on HALO to be not only the development of a new breed of positioning technologies, but more importantly be the start of a new era of intelligent, efficient and safe transportation for our nation, enabling sustainable economic growth. The enabling nature of HALO will stimulate the growth of many enterprises which will utilize HALO for transforming one of the pillars of our economy, the transportation infrastructure, to a green, safe and time efficient system. The effect of this transformation will be felt in all sectors of economy and in the overall improvement of the quality of life.

The technological advancements as a result of research on HALO are expected to deliver several immediate products. The primary products of the research on cost assessment of advanced ITS positioning systems are a set of decision support tools, prototype software and hardware in the hands of federal agencies required to estimate the federal investment required for precise positioning on the nation's roads. These deliverables would enable the federal government to assess the benefit of precise positioning, including in relation to high collision concentrations. Another deliverable will be the map of the area to be covered by HALO and cost estimate of achieving this objective. This information should enable private sector to plan and contribute to the overall deployment of HALO.

The primary product of research on positioning technologies will be the HALO technologies that will include either a fusion of existing methods, or completely new methods. In particular, we expect pseudolite based solutions to become ready for widespread deployment. In addition, GPS based solutions will be fused with pseudolite based solutions to provide complete coverage for advanced ITS applications.

Bibliography

1. *Phased array multipath detection: Power delay profile vs. information theoretic criteria.* Durkin, C.J. Durgin, G.D. s.l. : IEEE - Antennas and Propagation Society International Symposium, 2007.

2. *Achieving centimetre-level positioning accuracy in urban canyons with Locata technology.* Jean-Philippe Montillet, X. Meng, G. W. Roberts, A. Taha, C. Hancock, O. Ogundipe. s.l. : Journal of Global Positioning Systems, Dec. 2007.

3. *Network-based geometry-free three carrier ambiguity resolution and phase bias calibration.* FENG, Y., & RIZOS, C. 1, s.l. : GPS Solutions, 2009, Vol. 13.

4. *Array and Phased Array Antenna Basics.* Visser, Hubregt. 2005.

5. "2008 FEDERAL RADIONAVIGATION PLAN", National Technical Information Service, Springfield, Virginia 22161, DOT-VNTSC-RITA-08-02/DoD-4650.5

6. *Characterization of Driving Behaviors Based on Field Observation of Intersection Left Turn Across-Path Scenarios.f* Chan, C. Y. 3, s.l. : IEEE Transaction on Intelligent Transportation Systems, 2006, Vol. 7.

7. Final report of the National Surface Transportation Infrastructure Financing Commission entitled "Paying Our Way: A New Framework for Transportation Finance."

8. U.S. Department of Transportation, Volpe Center, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*, September 2001.

9. *Analysis of Vehicle Positioning Accuracy Requirements for Communication – Based Cooperative Collision Warning.* Steven Shladover, Swe-Kuang Tan. 3, s.l. : Journal of Intelligent Transportation Systems, 2006, Vol. 10, pp. 131-140.

10. *Cooperative Collision Warning Systems: Concept Definition and Experimental Implementation,* Raja Sengupta,S. Rezaei, S. Shladover, J. Misener,S.Dickey,H.Krishnan, J. of Intelligent Transportation Sys.,2007,vol.11, pp.143-155

11. *Kalman Filter Based Integration of DGPS and Vehicle Sensors for Localization.* Shahram Rezaei, Raja Sengupta, 6, s.l. : IEEE Transactions on Control Systems Technology, 2007, Vol. 15, pp. 1080-1088.

12. *Localization Using Virtual Antenna Arrays in Modulated Backscatter Systems,* U.S. Patent Provisional No. US61/067,398, Filed February 2008. Inventors: Kannan Ramchandran, Ben Wild and Art Tkachenko

13. *Localizing Tagged Assets Using Modulated Backscatter*, U.S. Patent Application PA4436US, February 25, 2008, Inventors: Ben Wild, Art Tkachenko, Kannan Ramchandran, Upamanyu Madhow.

14. *Study on Integrated Micro Inertial Navigation System/GPS for Land Vehicles.* J. P. Wang, W. F. Tian, Z. H. Jin,. s.l. : In Proc. IEEE Intelligent Transportation Systems, 2003.

15. GPS Operations Center. *United States Air Force Space Command.* [Online] [Cited: Jan. 26, 2009.] http://gps.afspc.af.mil/gpsoc/use_charts.aspx.

16. *Principles and Practice of GPS Surveying.* Rizos, Chris. Sidney, Australia : SNAP - School of Geometric Engineering, UNSW, 1999.

17. Dilution of Precision. *GPS World.* Langely, RB. May 1999.

18. *Using sampling and inverse distance weighted modeling for mapping invasive plants.* Roberts, E.A., Sheley, R.L., Lawrence, R.L. 3, s.l. : Western North American Naturalist, 2004, Vol. 64, pp. 312-323.

19. *Real-Time Differential Carrier Phase GPS-Aided INS.* Farrell, Jay, IEEE Trans Control Systems Tech, 2000, Vol.8.

20. *Safety and Capacity Analysis of Automated and Manual Highway Systems.* J Carbaugh, D. N. Godbole, R. Sengupta. 1-2, s.l. : Elsevier - Transportation Research Part C (Emerging Technologies), 1998, Vol. 6C.

21. *An Infrastructure Supported Concept for Automated Highway Systems. National Automated Highway System Consortium.* . D. N. Godbole, J. Misener, R. Sengupta, J. Tsao. s.l. : Milestone 2 Report, 1997.

22. *Intelligent Multi-Sensor Measurements to Enhance Vehicle Navigation and Safety Systems.* J. Allen, J. Britt, C. Rose, D. Bevly. s.l. : The Institute of Navigation, 2009.

23. *HAPPI - A High Accuracy Pseudolite/GPS Position Integration.* Ford, Tom and Neumann, Janet. Kansas City, MO : s.n., 1997. Proceedings of the Institute of Navigation GPS-97 Conference. pp. 1719-1728.

24. *Development and Testing of a Mobile Pseudolite Concept for Precise Positioning.* Raquet, J. and Lachapelle, G. Palm Springs, CA : s.n., 1995. Proceedings of the Institute of Navigation GPS-95 Conference. pp. 149-165.

25. *An Integrated Vehicle Positioning System for Safety Applications.* S. Weisenburger, C. Wilson. 2, s.l. : Journal of Navigation, 2000, Vol. 47.

26. *The Global Positioning System and Inertial Navigation: Theory and Practice.* s.l. Farrell, J. A & M. Barth, McGraw-Hill, 1999.

27. *An Efficient Dual-Frequency Ambiguity Resolution Algorithm For GPS-Based Attitude Determination.* Mongredien, C., J. Schleppe, G. Lachapelle and M.E. Cannon. 3, s.l. : Journal of Surveying Engineering, ASCE, 2008, Vol. 134.